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TEMPERATURE MEASUREMENT USING INFRARED IMAGING SYSTEMS

DURING TURBINE ENGINE ALTITUDE TESTING

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SUMMARY

A noncontact method of temperature measurement was used during altitude testing of an F-100 turbofan engine in the NASA Lewis Propulsion Systems Laboratory (PSL) to evaluate a new material in the exhaust nozzle over the operating range of the engine. Three identical infrared imaging systems, manufactured by Hughes Aircraft Company, were installed downstream of the engine, looking upstream at the nozzle internal surfaces. The components of each system included an imager with an internal argon-cooled detector which collected the infrared energy, and an electronics processor unit which first converted the detector output to a temperature-related gray scale and then created a color display. The infrared emissions of the exhaust plume were filtered out with an internal flame filter, allowing direct measurement of surface temperatures.

Because the hardware required physical protection from the hostile environment of the exhaust plume, the system installation in the test cell was quite involved. The imager (with a wide-angle lens) was mounted on a shock-protecting base to isolate it from any vibration of the test cell. It was enclosed in an aluminum box which was internally cooled with vortex coolers, and lined with acoustic foam-backed lead sheeting. The wide-angle lens was protected from the exhaust gases by a 6.5-in.- (16.51-cm-) diameter sapphire window which allowed 98 percent of the infrared radiation in the 3 to 5 μm range to pass through to the detector in the imager. Since the imager required high-pressure gaseous argon for detector cooling, a manifold system was designed to supply the argon from outside the test cell to the imagers inside. The systems were remotely operated from the control room about 100 yards (91.44 m) away, so all cabling was routed from the test cell through interconnect panels and cable trays to the processor in the control room.

During engine testing, as the throttle level of the engine and the temperature levels on the nozzle surfaces changed, the systems used an automatic temperature tracking mode so that the processors would adjust to capture the entire temperature range. Manual controls on the systems allowed for adjustment of emissivity, focus, sensitivity, and color scale. Both NTSC video data and digital data were recorded during testing. The NTSC signal was recorded continuously on VHS tape, and a personal computer recorded digital snapshots for post-run reprocessing. In spite of several difficulties with the installation and operation of the system, such as argon contamination, overheating, and procedural problems, the data gathered proved to be impressive as well as extremely valuable. The success of this method for this program led to many other applications in the engine test facility, including gas recirculation, external surface monitoring, and hydrogen flame detection, as well as enabled other test installations to build on an established knowledge and experience base.

INTRODUCTION

Lewis' Propulsion Systems Laboratory (PSL) is a testing facility where full-scale, airbreathing gas turbine aircraft engines are installed and tested at simulated altitude and flight conditions. The facility is capable of simulating altitudes up to 70 000 ft (21 336 m) and flight speeds up to Mach 3.0. Airflows up to 480 lb/s (217.7 kg/s) can be provided to the engine, and the exhaust gases are cooled and carried out of the test facility through an extensive exhaust system. The facility steady-state data system can measure and record over 1300 separate pieces of instrumentation such as thermocouples, pressure transducers, load cells, and rotational speed pickups.

In order to maintain the facility as a world-class testing resource, it is necessary to continually review and upgrade the techniques and hardware used in engine testing, and adapt existing or develop new test techniques and measurement systems. Since PSL is used primarily for experimental programs with unique requirements, the facility must continually adapt and prepare for these requests. In 1985, requirements for a particular turbofan engine test program included temperature measurements and heat transfer investigations of a newly developed exhaust nozzle cooling scheme. A new type of material for the internal surfaces of the exhaust nozzle was being evaluated, and because of the nature of the material, traditional methods of bonding thermocouples to the surface were ineffective. In addition, the large surface area to be monitored for the evaluation would have required far too many thermocouples than was practical. This led to the development of a noncontact method of temperature measurement using infrared (IR) imaging.

After considering two different IR systems available on the market, the system manufactured by Hughes Aircraft Company was chosen, and three complete, identical systems were purchased. The internal detectors in the Hughes systems were gaseous argon cooled, as opposed to liquid nitrogen cooled, which was expected to simplify the installation in the altitude chamber. Each system consisted of an imager, an electronics control unit, and several accessories to permit remote operation and data recording. Because of the intensity of the harsh environment in the test cell, the installation hardware was designed to provide sufficient protection for the system inside the test cell. Also, as the nozzle was moved during engine operation, the specific areas of interest inside the nozzle had to be captured in the field of view. Therefore, the three imagers were installed at fixed locations, viewing the nozzle from different angles. This report will detail the specifications, installation, and operation of these systems in PSL. In addition, the many problems encountered, and their appropriate solutions, will be explained.

APPARATUS

Facility

The Propulsion Systems Laboratory consists of two test chambers, 24 ft (7.32 m) in diameter and 39 ft (11.9 m) long, connected to a central air supply system. An engine is installed inside the chamber, directly connected to a pressurized air system by way of inlet piping and ducts. The altitude desired for a particular test condition is simulated by closing the test cell and evacuating the air with the exhaust (vacuum) machinery. The flight speed is simulated by providing pressurized air at the engine inlet at such a pressure that the correct ratio of the inlet pressure to the test cell pressure is developed. The engine exhaust is carried from the test cell through the exhaust collector/diffuser at the rear of the test cell and into the cooling systems before being directed to the atmosphere through the exhaust machinery. A bulkhead at the front of the test chamber separates the chamber from the inlet plenum. To provide true flight simulation, inlet air can also be conditioned for temperature, using either turboexpanders for low temperatures or heat exchangers for elevated temperatures. A schematic of the facility and a summary of the capabilities are shown in figure 1. A cutaway figure of the entire building, indicating the test chambers, the shop area, the control room, and the data room, is shown in figure 2.

For the first use of the infrared imaging systems, the engine under evaluation was a Pratt & Whitney F-100 afterburning turbofan. The engine installation in PSL is shown in figure 3. For this test, the standard round convergent-divergent exhaust nozzle was removed and replaced with a boilerplate, or non-flight-weight, two-dimensional, convergent-divergent thrust vectoring exhaust nozzle. The cross section of the nozzle was rectangular, allowing upper and lower flaps to move synchronously or independently to direct the thrust vector while still maintaining the necessary exit area and area ratio for optimum performance at various engine and flight conditions. A complete description of the testing techniques and facility modifications required for this test program can be found in reference 1.

Thermal Imaging System

The Hughes Probeye Thermal Video System, shown in figure 4, combines the technologies of infrared detection and image processing to provide a visual color display of thermal patterns and temperatures on any surface. Real-time temperatures can be displayed for on-line investigations, or the data can be recorded for later retrieval, reduction, and analysis. The basic components of each system are described as follows. Additional details can be found in reference 2.

Imager (or viewer head).—Housed within the aluminum enclosure of the viewer head (shown on tripod in fig. 4) are the essential optical, electronic, and mechanical elements of the system, including mirrors, a motor, a detector array, a cryostat assembly, and signal processing devices. The infrared radiation from the target enters the front of the viewer through a silicon window in the front of the aluminum housing. The beam of radiation reaches a spinning mechanism which has 10 double-sided mirrors, each canted at a slightly different angle to provide 10 distinct reflections. Each of the 10 reflected scans is directed to another mirror which reflects them to a six-element indium antimonide (InSb) detector, creating 60 scan lines. The detector array is cooled to 87 K (-187°C) with high-pressure gaseous argon expanded through a cryostat. The argon can be supplied by either a small 5000-psi (34.5-kN/m^2) cylinder attached directly to the body of the viewer, or by a larger 2500-psi (17.24-kN/m^2) K-bottle through hoses or piping. The signal output of each detector element is proportional to the infrared energy collected from the target. The detector outputs are amplified, conditioned, and directed two ways. One way is via the output cable going to the external electronic processor, and the other path is to an array of six light emitting diodes (LED's). The LED output is reflected off the backside of the spinning mirror assembly to a stationary mirror assembly to provide an LED visual display in the viewer's rubber eyepiece. Thus, a visual image is created coincident with what the detector assembly is viewing. A more extensive technical discussion of this type of system can be found in reference 3.

The system specifications are as follows:

Viewer external operating environment, $^{\circ}\text{F}$ ($^{\circ}\text{C}$)	50 to 104 (10 to 40)
Spectral range, μm	2 to 5.6
Scan rate, frames/sec	20
Focus range, in. (cm)	3.94 (10) to infinity
Spatial resolution, deg	0.126 horizontal and vertical
Field of view, deg	15 horizontal by 7.4 vertical
Field of view, with wide-angle lens, deg	60 horizontal by 30 vertical
Line rate, lines/sec	1200
Display resolution, lines	60/frame, interpolated to 120

For this test application, the field of view was enlarged to 60° horizontal by 30° vertical by using a wide-angle lens which attached directly to the front of the viewer body. In addition, to enable viewing through the exhaust plume to the nozzle surface, a flame filter was inserted in the wide-angle lens. The flame filter is a notch filter which filtered out the wavelengths of the carbon dioxide and water vapor emissions. Both the wide-angle lens and the flame filter were available from Hughes as accessories to the Probeye system.

Processor.—The analog signal from the detector outputs in the viewer head is directed to the processor (on right, fig. 4) by a cable with a 21-pin connector at each end. The signal is split, and an analog-to-digital converter inside the processor creates a digital signal from one of the analog outputs for input into an external computer interface unit. An image processor reformats the other analog signal to create a 120-line, 4-bit resolution, 16-color gray scale video signal, and is further reformatted into a 300-line, 256-pixel, NTSC video format to allow display on a standard color monitor and recording with any video recorder. The processor also houses the power supply for the system.

All the operations of the system are executed from the keyboard on the front of the processor, shown in greater detail in figure 5. The keyboard functions can be described as either input or output functions. Input functions describe the environment to the system, such as emissivity, temperature range, and sensitivity. Output functions determine display characteristics such as color scheme, automatic tracking modes, zoom, and frame freeze. A 3-in. color monitor on the front of the processor displays the color-enhanced image.

Remote keyboard.—Each system has a remote keyboard which exactly duplicates the keyboard on the front of the processor (shown between viewer and processor in fig. 4). This enabled operation of the system from the PSL control room while the processor and other components of the system hardware were contained in the basement data room.

Remote focus control.—The remote focus control permitted adjustment of the focus from either the processor or the remote keyboard. The control drives a servomotor device within the viewer to provide true optical focus. This device was located in the control room at the remote keyboard.

VHS format video recorder with wired remote.—A VHS format recorder was used to continually record all video output. The recorder was placed in the basement and controlled with a wired remote from the control room.

Computer interface unit.—This unit, containing an IEEE-488 interface, allowed the digital signal from the processor to be fed to a computer system (PC) for further recording, postprocessing, and display.

Video distribution amplifier.—This device, placed downstream of the video recorder, amplified the video signal to provide up to eight high-quality outputs for inputs to other monitors or recording devices. This eliminated the signal degradation associated with "daisy chaining" several components together.

Monitors.—For each system, a 19-in. (48.26-cm) rack-mountable color monitor, a 21-in. (53.34-cm) tabletop color monitor, and a 5-in. (12.7-cm) remote monitor were placed in strategic locations to allow visitors to observe the infrared image without interfering with the operation of the system. The signal for each monitor was supplied from the distribution amplifier.

Beta format recorder.—A Beta format recorder was included because the customer specifically requested this format for the data. NASA's permanent record format was VHS.

IBM PC-AT.—This was used for recording, manipulating, displaying, and outputting the digital data received from the viewer cable. To record the digital data, the current display on the processor was captured as a single frame (or snapshot) and transmitted to the PC by way of an IEEE-488 interface in the computer interface unit. The first data transmitted contained reference information necessary to coordinate data format and transmittal. Following the reference data were data from the 256 pixels of each of the 60 scan lines, and environment information such as emissivity, minimum temperature, sensitivity, and ambient temperature. With Hughes-supplied software and NASA-developed software, the PC stored the digital information on floppy disks and allowed post-test analysis and display of the data.

Figure 6 shows the configuration of all the components in relation to each other in the facility. To make it easier to operate any of the components, an interconnect patchboard was fabricated to allow the output of any component to be easily connected to the input of another. The schematic of this patchboard is shown in figure 7.

Each of the systems was calibrated by Hughes Aircraft Co. in Carlsbad, California, according to specific requirements defined by Lewis. The IR processor can store different "temperature look-up tables" to convert the IR energy to temperature for display, depending on the specific accessories (filters, windows, etc.) in the path of

the signal. To generate these tables, each system must be calibrated using a blackbody radiation source, and the specific cable, accessories, and/or hardware in place. For the PSL application, four look-up tables were generated to account for different configurations involving the sapphire window, flame filter and wide-angle lens, and a 100-m processor-to-viewer cable. The tables programmed into each system are shown in table I.

INSTALLATION

Figure 8 shows the installation of one of the three infrared viewers, which were located inside the exhaust collector in the test cell, and were positioned to look upstream inside the exhaust nozzle. After extensive evaluation of axial distances, changing angular position of the nozzle surfaces, and obstructions in the field of view, three positions in the exhaust collector were chosen. At each location, a port was cut out of the collector, and a sapphire window installed in a retaining mount. Sapphire demonstrates excellent transmissive qualities in both the visible and infrared spectrum ranges (ref. 4). Since the exhaust gas velocity was exceptionally high and the environment inside the collector particularly harsh, it was necessary to provide physical protection for the viewers. Sapphire could adequately provide this protection without greatly compromising the infrared signal, since it transmits in the 2.0 to 5.6 μm range of the electromagnetic spectrum. The sapphire was 0.37 in. (0.94 cm) thick, and could withstand a pressure difference of 5 psid (3.4 N/cm^2).

A drawing of the window mount hardware is shown in figure 9(a), and the individual pieces are shown in the photograph of figure 9(b). The whole structure installed in the exhaust collector is shown in figure 9(c). The hardware was designed so that the window would be canted 15° off the normal axis of the front of the viewer to eliminate the cold reflection phenomenon known as the "Narcissus effect" in which the detectors (which are very cold) see their own reflection from the sapphire window. (See ref. 3.) Each window mount had cooling water circulating through an inner (gaspath side) shell to minimize heat loads from the exhaust plume. A flexible bellows allowed for thermal expansion between the water-cooled inner shell and the uncooled outer shell. Initially, the window housing was designed to hold a 6.5-in.- (16.51-cm-) diameter window, but each was later modified to accept smaller windows. To prevent the buildup of exhaust gas particles on the surface which could adversely affect the accuracy of the temperature measurements, additional cooling air was provided to both sides of the window to act as an airwash of the surfaces. Each window was sandwiched in its housing between two flat neoprene gaskets, and surrounded by a high-temperature O-ring at the circumference. Compression of the gaskets was controlled by metal shims, and the window was allowed to float within its housing as the metal of the housing changed dimensions with temperature.

Inside the test cell, each viewer was enclosed in an air-cooled, thin-walled aluminum box to protect it from the surrounding elevated temperatures inside the test chamber. The Probeye system is designed to operate at ambient temperatures below 104 $^\circ\text{F}$ (40 $^\circ\text{C}$), and test cell temperatures near the exhaust collector greatly exceeded this. A schematic and photograph of an enclosure are shown in figure 10. The cooling was provided by a vortex air cooler, which worked exceptionally well. When the engine and facility are in operation, there is significant mechanically and acoustically induced vibration in the test cell, and since even the smallest movement would distort the visual output as seen on the monitor, each enclosure had a double vibration isolation mounting for the viewer. Each enclosure was supported by a unique positioning mount which allowed for finer adjustments in all planes. A rubber boot was used to join the window mount to the enclosure to ensure the effectiveness of the vortex cooler, and to prevent any infrared radiation from other sources, such as the test cell lights, from entering the imager.

As mentioned previously, each imager required high-pressure argon to cool the internal detector array. By design, small 5000-psi (34.5- kN/m^2) bottles could be fixed directly at the viewer to supply the argon, but because of safety reasons, these high-pressure cylinders could not be located inside the test cell. Larger 2500-psi (17.24- kN/m^2) K-bottles were fixed outside the test cell, and a manifold system of valves and stainless steel

tubing was developed to transport the gas from outside the test cell to the viewer. (See fig. 11). The requirements for the gas specified prepurified argon with a minimum purity of 99.998 percent and a maximum dew point of -76°F (213 K) (see ref. 2). To guard against any sediments or dust getting through the lines into the viewer and possibly damaging the mechanical parts, a fine-mesh bronze filter was installed in the line. Further, to ensure the dryness of the argon, a desiccant was placed in the line upstream of the viewers. Specific procedures were developed for purging and evacuating the lines to rid the system of particulates and moisture. Two argon supply bottles were installed outside the test cell, and an isolation valve could be positioned to draw gas from either of the bottles. One 2500-psi (17.24-kN/m^2) bottle could supply enough high-pressure gas for about 15 hr of testing. According to the system specifications, the cryostat inside the viewer would be effective only if the supply pressure of the argon was above 900 psi (6.21 kN/m^2). A pressure transducer was installed at each bottle and cabled to the data system to permit on-line reading of the argon pressure.

Finally, the exterior metal surfaces of the nozzle which were in the field of view were coated with a high-temperature flat black paint of known high emissivity to facilitate any external temperature monitoring with the IR systems and to reduce reflections which would interfere with an accurate reading.

SETUP AND OPERATION

The application, installation, and operation of these systems in this environment were replete with various challenges, most of which were successfully overcome. It was necessary to become familiar with the laws governing infrared radiation and measurement in order to effectively use the equipment to record meaningful data. As the work progressed from the system selection through to the installation, and the complexity of the project grew, it was clear that detailed setup procedures had to be developed. The test program requirements stressed the need for correct simultaneous operation of all three IR systems.

To accurately position the viewers to capture the complete target, a unique and extremely successful procedure was used. Although the viewer boxes were mounted in fixed positions, they were designed to allow for finer adjustments in three axes for better positioning. To determine the final position, the target and some surrounding surfaces were outlined using low-voltage electrical "heat tape" which, when activated, reached a temperature of about 110°F (43.3°C). A wide-angle lens was put on each IR system (a flame filter was not used), and the outline of the target as defined by the heat tape was clearly visible using the appropriate temperature look-up table on each system. The position of each imager in its mount was adjusted and fixed in a final place.

For daily test runs, the electronic setup involved correctly cabling and patching the components, and verifying the power supplies. The pre-run mechanical setup involved evacuating and purging the argon lines for several hours. A sufficient supply of argon was verified, and all valves and connections were checked for leaks and correct positions. All valves inside the test cell were opened, but the main shutoff at the K-bottle outside the test cell remained closed until the system was needed. The on-off switch on the camera was verified to be on, and the brightness and contrast controls were verified to be in the correct position. The imagers were focused by placing a heat source such as a soldering iron in the field of view of each imager, and remotely focusing the system from the control room to get the optimum display on the control room monitors. The color image produced by the IR system was not easily recognizable, especially for those people who were not very familiar with the hardware in the test cell. Before the imagers were installed in the test cell, a 35-mm camera with a 30° by 60° wide-angle lens was used to take pictures of the exhaust nozzle from each IR imager port location. The nozzle actuation system was used to set the nozzle at specific exit areas, area ratios, and vector angles that were expected during the altitude test. The photos were compiled in a book and used during the runs to compare the on-line IR image with the actual visual image. This was a valuable tool for explaining the nozzle conditions and temperature distribution during the test runs. Figure 12 shows an example of both the IR image and the visual image of the nozzle at a set condition of area ratio, exit area, and vector angle.

Operation of the systems during engine testing was labor intensive, since the temperature levels of the exhaust nozzle changed rapidly with changing flight conditions and engine throttle settings. At engine light-off and idle condition, the surface temperatures in the exhaust nozzle were fairly low, below 400 °F (204.4 °C). Since the IR systems were not calibrated to such a low temperature with the flame filter and wide-angle lens, the accuracy at these low temperatures was not reliable, although clear images were visible on the monitors. As the temperature rose, the IR processor was placed in an automatic mode which would track the highest temperature in the field of view and adjust the temperature display levels according to the operator selected sensitivity. As the temperature increased even further, the operator reduced the temperature sensitivity to capture more of the field of view. For example, at idle setting, the sensitivity would be set to 10 °F (5.55 °C) per color, giving a full range of 160 °F (88.9 °C) across the whole color range. The low temperature would be set at 400 °F (204.4 °C), putting the highest temperature at 560 °F (293.3 °C). Just past idle, much of the hardware was at a temperature in this range. As the engine throttle was advanced and the hardware temperature began to increase, the automatic mode would track the highest temperature and adjust the display colors accordingly. At times, the sensitivity was adjusted as the minimum-to-maximum temperature spread increased. At higher power conditions, the sensitivity was set to 50 °F (27.7 °C) per color, thus raising the maximum detected temperature to a higher level.

The video signal was recorded continuously. The digital signal was recorded at specific engine and nozzle settings. At the higher temperature conditions, a method referred to as "frame stacking" was used; here, three consecutive readings of overlapping temperature ranges were recorded with a very high sensitivity to ensure that the entire wide range of temperature was captured with high accuracy.

As a check on the validity of the temperature measurements, a reference target of the same material as the internal nozzle surface was fabricated and instrumented. A thermocouple was installed inside a small slab of excess nozzle material by drilling a small hole into the edge and butting the head of the thermocouple as close to the outer surface as possible. This small slab was fixed to the trailing edge of the exhaust nozzle such that its front surface was exposed to the high gas temperatures in the same way as the actual nozzle surfaces. Figure 13 shows a sketch of the reference target construction. During engine operation, the cursor on the IR system processor monitor was placed on the target in the field of view, and the temperature was compared with the thermocouple readout on the facility data system. At high temperatures, as the amount of total radiation over the whole infrared spectrum increased, the error of the temperature measurement was reduced, and the reading of the IR system was in good agreement with the target sample thermocouples.

DISCUSSION OF RESULTS

Overall, the installation and operation of the systems satisfied the objectives of the research program. The 16-color output on the monitors was impressive. The video data displayed during the test runs uncovered critical data, providing valuable information about the thermal patterns inside the nozzle to allow engineers and designers to easily and immediately identify the characteristics of the cooling system and make prompt adaptations to the design. The systems were unique and indispensable measurement and monitoring tools which have enhanced the testing techniques used in the PSL facility.

The reference target and blackbody calibration checks revealed that the accuracy of the temperature readings on the IR systems could be very high (+3.0 to -1.5 percent), depending on the temperature level of the hardware. As testing continued, the attention shifted from determining temperatures to observing the thermal patterns and relative temperature differences, and the temperature accuracy became a less critical concern.

Although the systems have provision for showing operator-entered alphanumeric information on the processor display, this proved complex and cumbersome. Therefore, to correlate the IR data with the engine

operation, the clocks on the IR systems were synchronized with the facility data system clock, and engineers could then match the test run log and event summary, the data from the facility data system, and the Probeye recorded data using time and date as the common item.

The remainder of this discussion will address the several problems and solutions associated with the installation and operation of the systems in PSL.

Argon System

Once the systems were installed and operational, altitude testing began. After about 20 hr of testing, the IR systems began to show signs of low argon pressure. Six wide horizontal bars gradually appeared on the monitor characteristically indicating that one detector at a time became too warm to operate correctly. However, the transducer at the argon supply bottles indicated approximately 1100 psi (7.59 kN/m²), which is greater than the 900-psia (6.21-kN/m²) limit stated in the Hughes Probeye Operating Manual. A pressure drop in the line between the supply and the viewers was assumed, and a transducer was installed in the line as close as possible to the viewers to investigate this situation. Although a slight pressure drop was detected, the argon entering the viewers was still greater than 1000 psi (6.9 kN/m²), yet the system would not perform correctly. When the isolation valve was switched to draw gas from the other fully pressurized supply bottle, the image came back and the system began operating normally. The conclusion was that at least 1100 psi (7.59 kN/m²) of argon pressure was needed for this installation, and it was necessary then, during each pre-run setup to make certain that there was at least one fully pressurized bottle hooked up to the farm system.

Another argon manifold system problem focused on contamination in the lines. During the installation of the system, the probability of oil, moisture, dust, or other particles getting in the line was naturally very high. If these contaminants entered the viewer, the movement of the mirror assembly would be hindered. In spite of great care to purge and vacuum the lines and the viewer, two contamination problems were discovered. First, the presence of moisture became evident by "detector freeze," where one or more bands (corresponding to one or more detectors) on the monitor would appear to be frozen (i.e., still and unmoving). As the argon gas was expanded through the cryostat, the moisture would freeze and the ice crystals would interfere with the detectors. This problem was easily rectified by heating up the viewer with a hot air source such as a heat gun until the ice melted and the moisture evaporated.

A second contamination problem was traced to the silica gel desiccant in the argon line. The desiccant pellets were housed in a small cylinder in the line, downstream of the isolation valve and upstream of the check valves. One end of the cylinder could be unscrewed for emptying and replacing the desiccant material. If this end were screwed on too tight, or if the cylinder were overfilled, the cap would crush the pellets to a powder. Since the particle size of the powder was smaller than the bronze filter, the powder would travel into the viewer where it would interfere with the cryostat and the mirrors. The only way to prevent this was to be careful to not overtighten the end of the desiccant cylinder.

O-Ring

One minor problem that surfaced early in the installation was easily corrected with procedural checksheets. At the fitting on the viewer where the argon line attached, a small rubber O-ring (approx. 0.25 in. (0.0635 cm) diam) was used to seal the area around the opening. Often, as the argon line was disconnected, the O-ring would fall out unnoticed. If the line was reconnected, and the O-ring was gone, the argon gas would leak at the fitting because of the poor seal. Sometimes a hissing noise was immediately detected, but other times the problem was not discovered until it was noticed that the argon supply pressure had dropped unusually fast. To

prevent this problem, all technicians were carefully briefed on proper procedures, and the checksheets were modified to alert the user to check the position of the O-ring any time the argon line was disconnected.

Processor-Viewer Mismatch

Because of the nature of the electronics and system cable length, each processor could only be used with the viewer that it was initially calibrated with. If a processor and viewer were mistakenly mismatched during the pre-run setup, the image on the monitor in the control room would display jagged edges, wavy lines, or a persistent quivering or shaking. This indicated that the internal timing of the rotating mechanisms was off. In this case, the system would be shut off, the correct processor matched to its viewer by serial numbers, and the system turned back on.

Overheating

Viewer enclosure.—During some very high temperature conditions, the inside of the viewer enclosure would exceed its limit of 100 °F (37.8 °C), creating a condition hazardous to the detector and its electronics. The small vortex cooler was replaced with a larger one, and the problem was easily eliminated.

Melted wide-angle lens.—One evening, while observing the control room monitors during a high-temperature condition (about 3000 °F (1648.9 °C) gas temperature), a wide-angle lens was severely damaged when it was subjected to intense radiation passing through the highly transmissive sapphire window. Fortunately, only the front piece of the hard plastic lens housing was melted, and it was easily replaced. To prevent this problem, a radiation shield was fabricated from aluminum sheeting and fitted over the plastic piece of the lens housing. In addition, some supplemental cooling air was directed to the lens area inside the viewer enclosure as well, and thermocouples were installed to facilitate temperature monitoring.

Sapphire Window Cracking

The most perplexing problem during this program was the cracking of the 6.5-in.- (16.51-cm-) diameter sapphire windows. After a minimum-maximum-minimum temperature transient, a thick dark jagged line appeared across the image on the monitor. Initially, it was assumed that it was an unusual but genuine thermal pattern on the target surface. However, when it stayed constant with a change in temperature level, a cell entry was made to investigate the peculiar pattern. The sapphire window inside the exhaust collector was found in its holder with a large crack across its entire diameter. Because of the possibility that the window cracked from insufficient cushioning during a pressure surge, the existing thinner gaskets in the window holder were replaced with thicker ones. The window was then replaced with a new one, which also cracked, but at a different engine condition. To study the problem even further, a quartz window was installed in place of a sapphire window, but it did not crack when conditions were repeated. A steel blank-off plate, instrumented with pressure taps and thermocouples on both sides, was installed in place of the sapphire window, and the engine conditions were duplicated. The recorded data revealed no unusual thermal or mechanical (pressure) stresses on the plate, and the cause of the cracking windows remained a mystery. A third window in a different location broke in a particularly spectacular fashion. Shown in figure 14, the sapphire was completely shattered, but still completely intact in its holder, indicating it may have been squeezed in by uneven thermal growth relative to the holder. After this third window broke, all of the large 6.5-in.- (16.51-cm-) diameter windows were removed, and the window holders were modified to accept smaller 2.5-in.- (0.635-cm-) diameter windows, as shown in figure 15. This finally eliminated the cracking window problem, but slightly compromised the field of view.

Miscellaneous

The test program continued for several months, during which the IR equipment was aggressively used in the harsh environment. At the completion of the program, the three systems were removed from the test cell, and successfully used in other areas for other test programs. During one of these other tests, one of the viewers failed to work; the rubber belt that drives the mirrors had all but deteriorated and was cracked in dozens of places, rendering it incapable of driving the mirrors. At that point, the three units were shipped back to Hughes where they were inspected, overhauled, and recalibrated.

OTHER APPLICATIONS

The nozzle program in PSL was by far the most demanding application for the Hughes Probeye systems. Other programs were much less complicated in installation, operation, and environments. Of course, the amount of knowledge gained during this first program overwhelmingly simplified the use of the systems in other programs. For one program, two viewers were set up on tripods outside the test cell, looking at the outside surfaces of an engine through sapphire windows installed in the wall of the chamber. All that was needed for each viewer was a small 5000-psi (34.5-kN/m^2) argon cylinder which attached directly to the viewers, eliminating the complex argon farm system. The existing cabling was used, and the system was operated from the control room. No enclosure or auxiliary cooling was needed.

One of the systems was used in the second chamber of the PSL facility to observe a hydrogen flame, which is invisible to the naked eye and only transmits in the low end of the infrared range of the Hughes system. The viewer was mounted to a pedestal using modified hardware from the previous nozzle test. Even though it was inside the altitude chamber, the viewer was not in the direct path of any harsh exhaust, so a sophisticated enclosure and cooling scheme was not necessary. However, the main roadblock in this application was cable length between the viewer and the processor: the second test chamber was an additional 30 ft (9.14 m) along the cable tray path. Two cables were spliced together to cover the distance, but the system would not work with the extra long cable. After trying several equally ineffective alternate paths and cable lengths, the shortest possible cable was strung across the shop from the control room to the test cell, bypassing any cable trays.

For future PSL tests, three new Hughes systems were purchased to replace the older systems. Touted as top-of-the-line products, the new systems have a significant number of improvements and capabilities over the older ones. The most significant refinement is the replacement of the high-pressure-gas cooling scheme with a completely electric cooling scheme. This will significantly simplify any future installation by eliminating any argon supply system. In addition, the data recording capabilities and postprocessing have been greatly enhanced, resulting in a very fine measurement tool and system for the Lewis Research Center.

CONCLUDING REMARKS

Three infrared imaging systems were used successfully to monitor thermal patterns and record temperatures of the internal surfaces of an F-100 turbofan engine exhaust nozzle during simulated altitude testing at NASA Lewis Research Center's Propulsion Systems Laboratory. This report presents the details of the components of the system, the installation and operation of the systems, and the numerous problems encountered during the use of the systems.

The installation of the viewers (imagers) in the exhaust collector of the test cell was particularly complex in order to provide the necessary protection from the harsh exhaust gas environment. Sapphire windows, 6.5 in. (16.51 cm) in diameter and 0.37 in. (0.94 cm) thick, were installed in the facility exhaust collector to allow the

infrared imagers to view the test hardware. The design of the window mount required significant modification to accept smaller, thinner windows after three of the larger sapphire windows fractured in the extreme environment. The design of the viewer supports was adequate, giving the needed ability to aim the cameras as required, and the protective vibration-isolating enclosures functioned as intended, providing the viewers with sufficient protection from shaking and heat. The inside of the enclosures required more cooling than initially expected, as evidenced by a severely melted wide-angle lens exposed to very high temperatures. To further protect the plastic casing of the wide angle-lenses, aluminum radiation shields were fabricated. The argon distribution system performed acceptably well, as long as painstaking efforts were made to ensure both argon purity in the line and adequate supply pressure at the viewers. The on-line operation of the systems was labor intensive, requiring considerable interaction from the system operator. In addition, it was imperative that the operator be familiar with infrared theory in order to assess whether valid data was being recorded.

The infrared imaging systems have greatly augmented the testing capabilities in the Propulsion Systems Laboratory, and have since been used aggressively in a variety of test programs. Lewis now possesses a great deal of experience and expertise in the application of thermal imaging systems in extremely harsh environments. For future tests in the facility, more advanced systems have been purchased, and with the experience gained, the proficiency will continue to grow, giving the testing community a reliable and notable resource.

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2. Probeyetm Thermal Video System Series 4000 Operation Manual. Hughes Aircraft Company.
3. Lloyd, J.M.: Thermal Imaging Systems. Plenum Press, New York, 1975.
4. Wolfe, W.L.; and Zissis, G.J., eds.: The Infrared Handbook. The Infrared Information and Analysis Center, Environmental Research Institute of Michigan, The Office, Washington, D.C., 1978.

TABLE I.—TEMPERATURE TABLES FOR IR SYSTEMS

Temperature name shown on system	Accessories	Temperature range
C - 950 - 100	None	-20 to 950 °C
F - 1700	None	-4 to 1742 °F
F - 1700 - 60	Field of view lens (60° by 30°)	-4 to 1742 °F
F3K - 60 - FLS	Field of view lens (60° by 30°) Flame filter Sapphire window	392 to 3000 °F

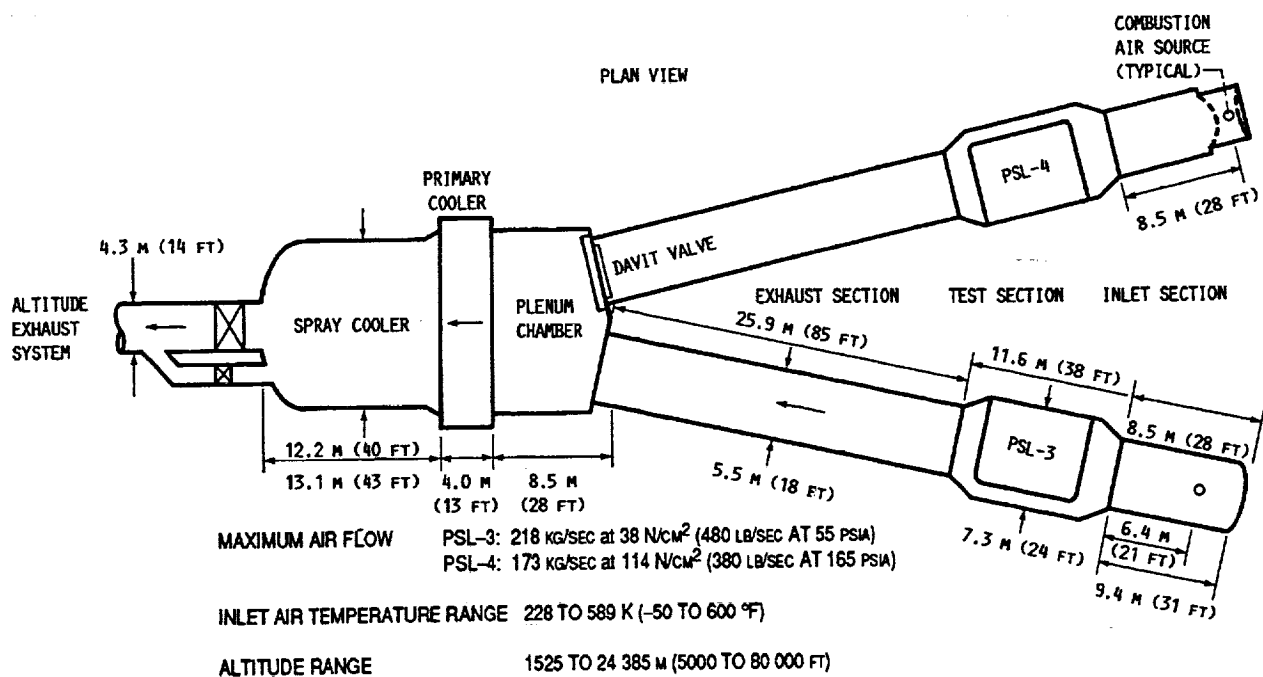


FIGURE 1.—PROPULSION SYSTEMS LABORATORY LAYOUT AND CAPABILITIES.

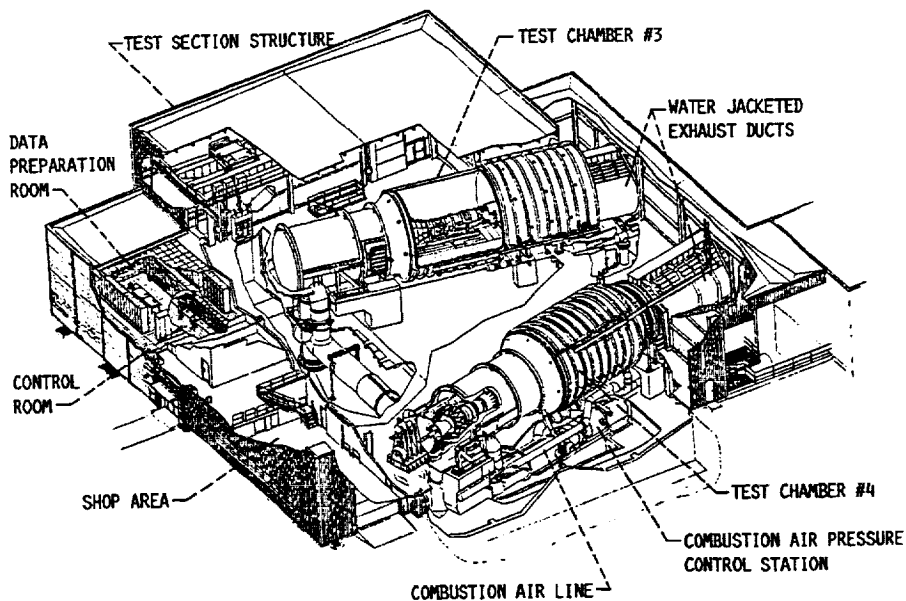


FIGURE 2.—CUTAWAY VIEW OF PROPULSION SYSTEMS LABORATORY.

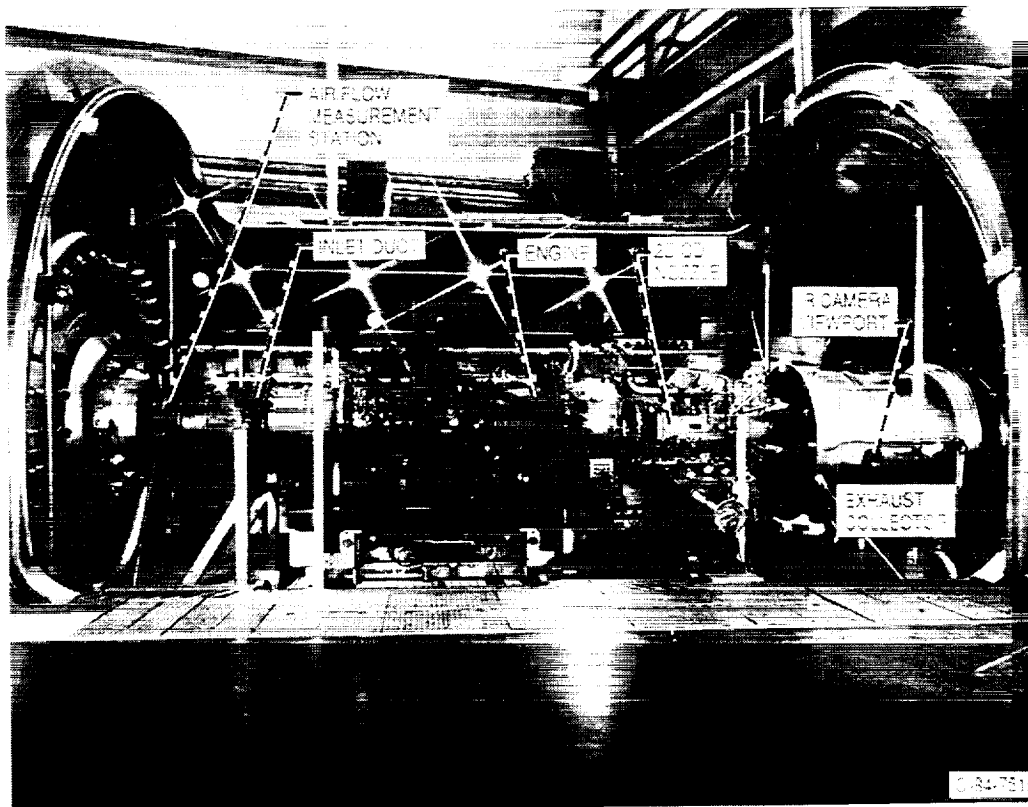


FIGURE 3.—OVERALL INSTALLATION OF TEST HARDWARE IN TEST CELL 3.



FIGURE 4.—HUGHES PROBEYE THERMAL VIDEO SYSTEM.

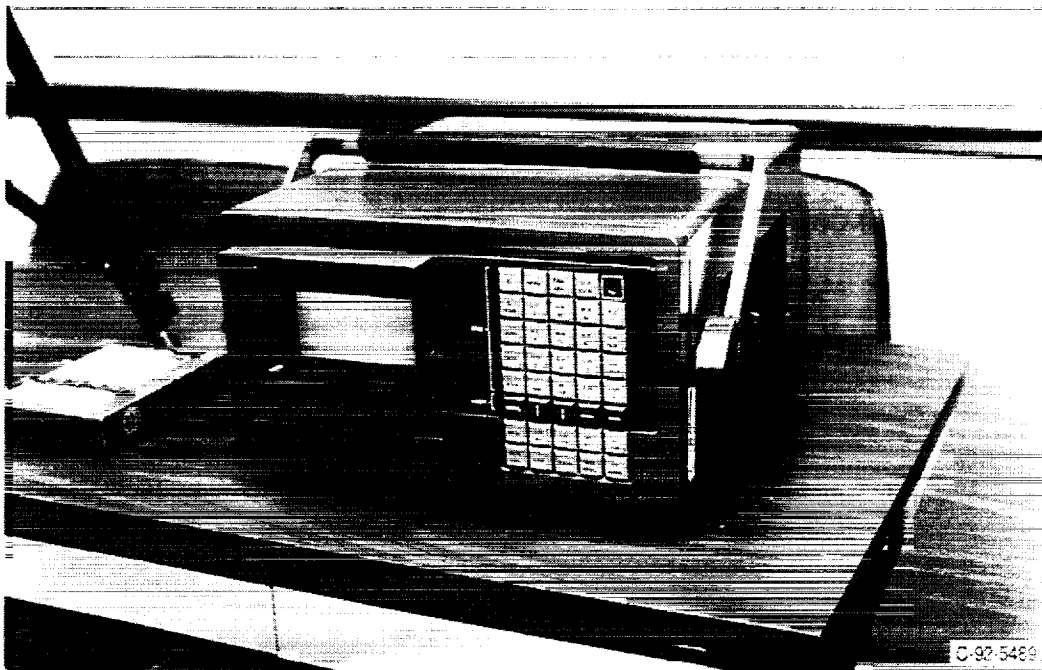


FIGURE 5.—PROCESSOR KEYBOARD.

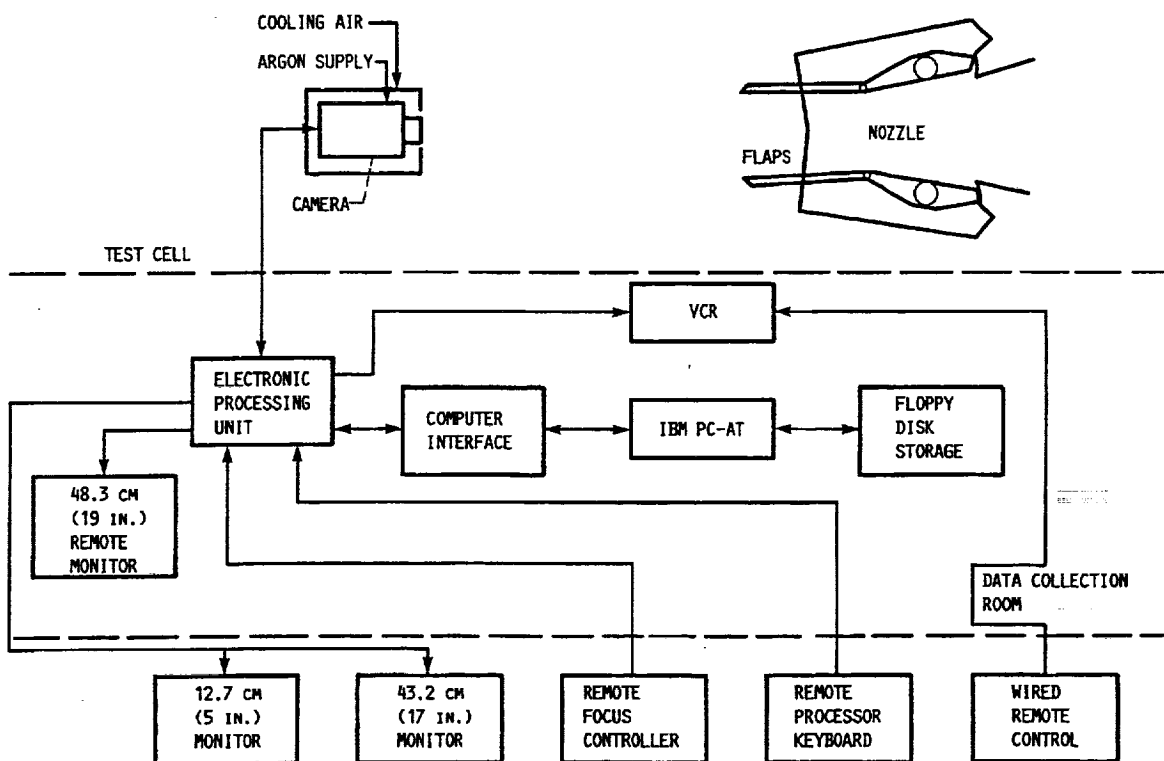


FIGURE 6.—TYPICAL INFRARED SYSTEM CONFIGURATION IN PSL.

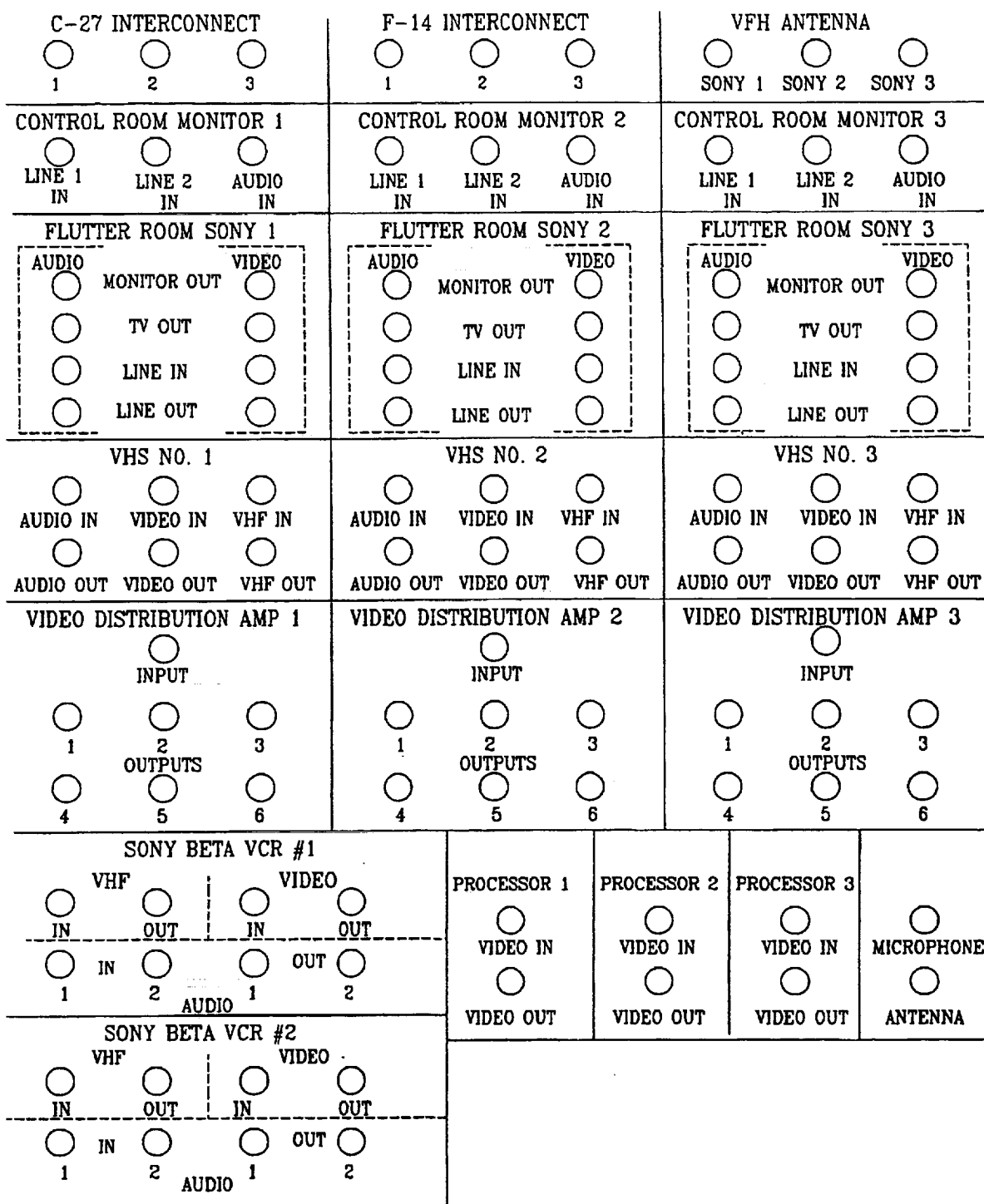


FIGURE 7.—PATCHBOARD SCHEMATIC.

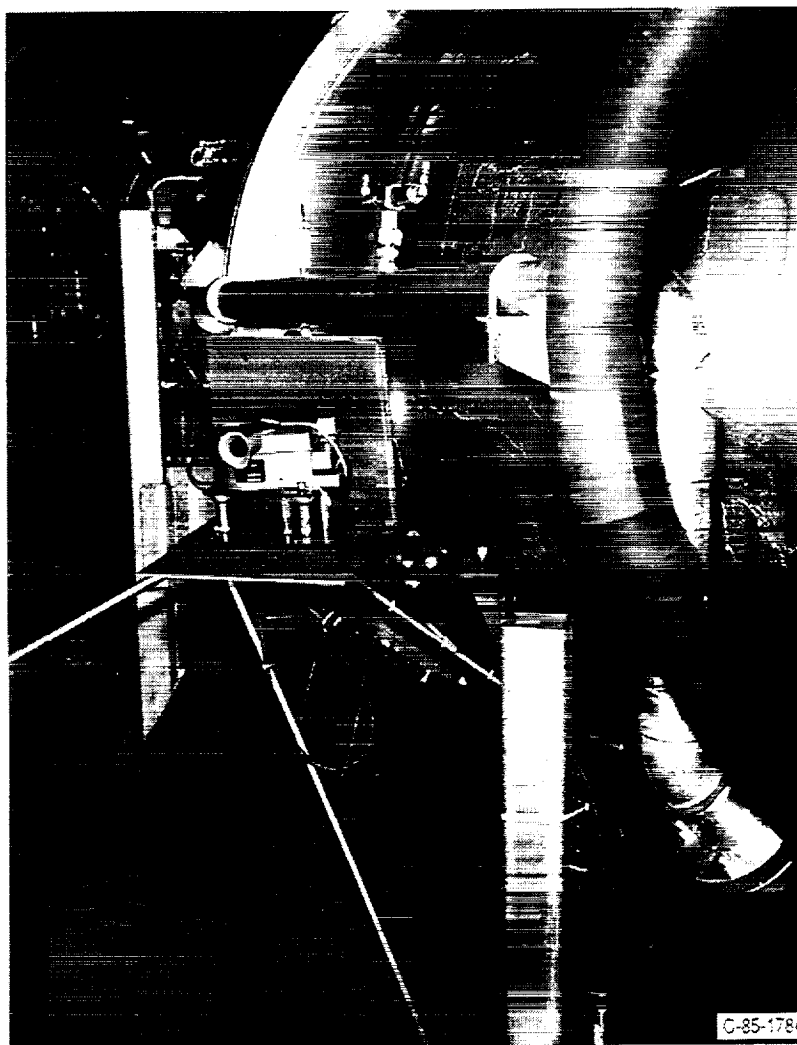
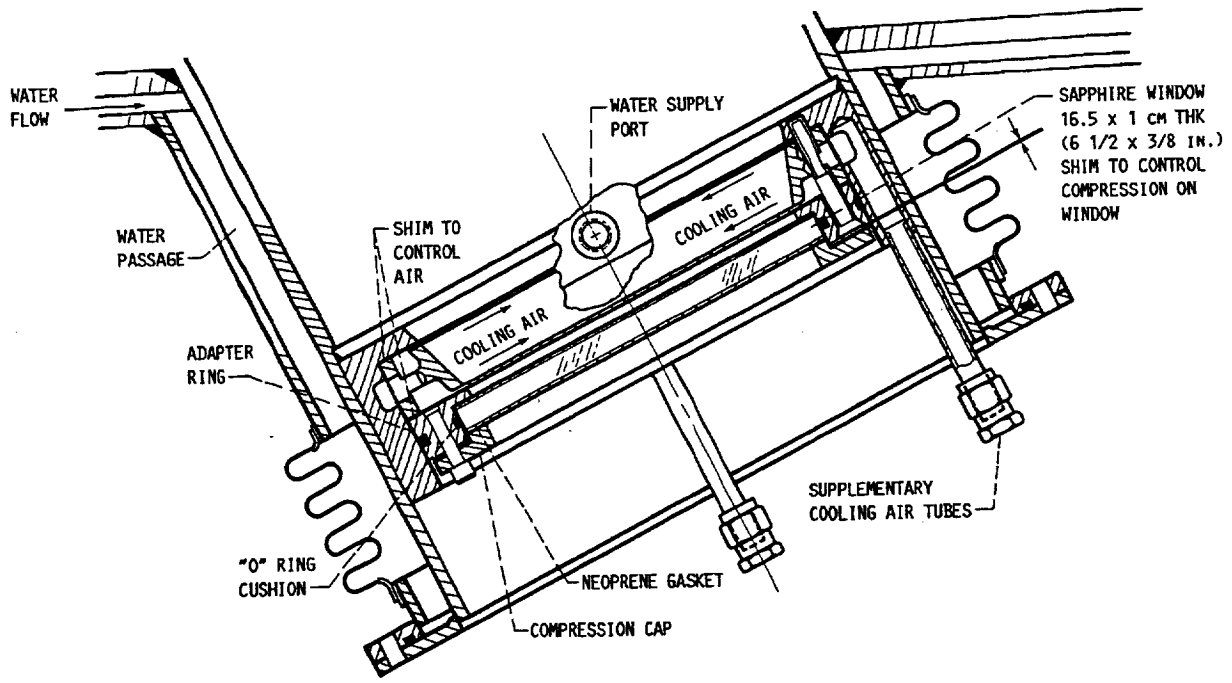
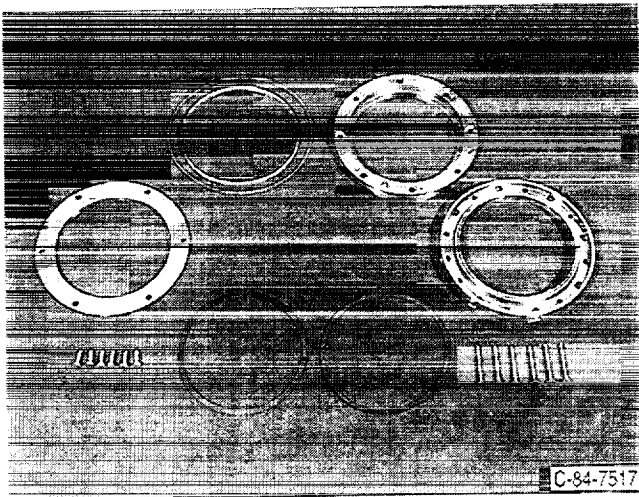


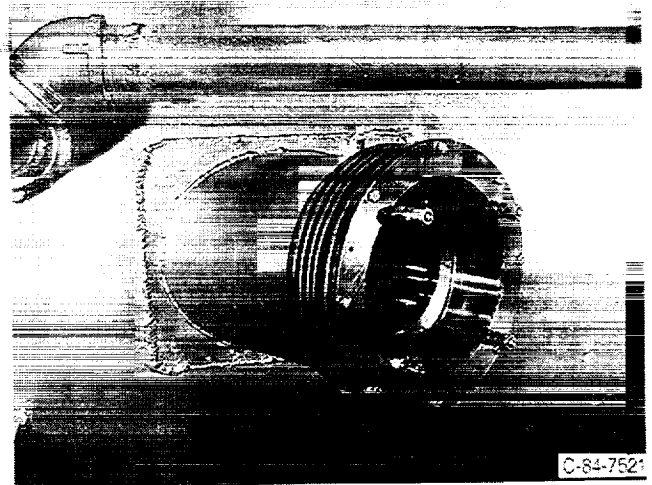
FIGURE 8.—INFRARED VIEWER INSTALLATION IN PSL



(A) HARDWARE.

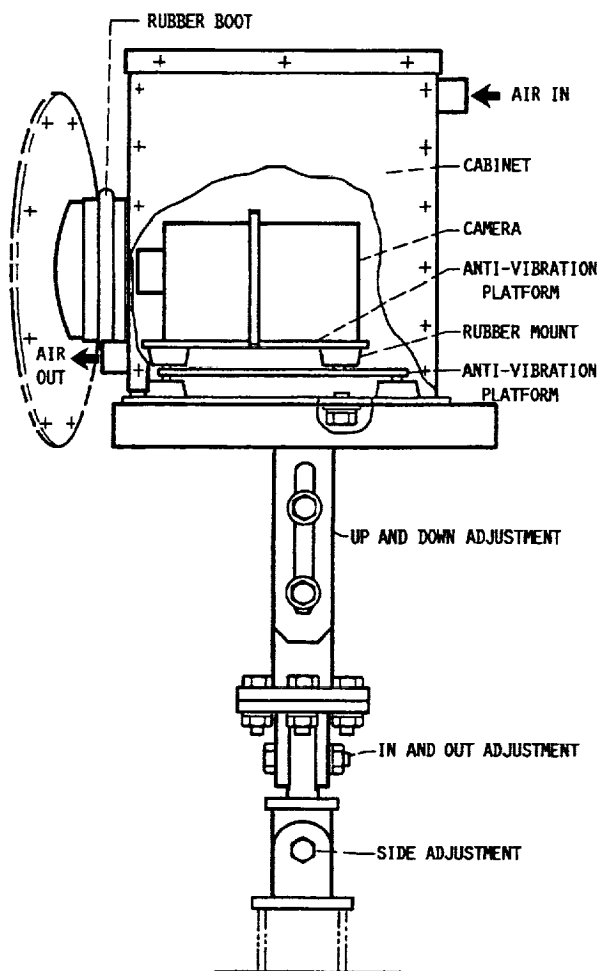


(B) HARDWARE PIECES.

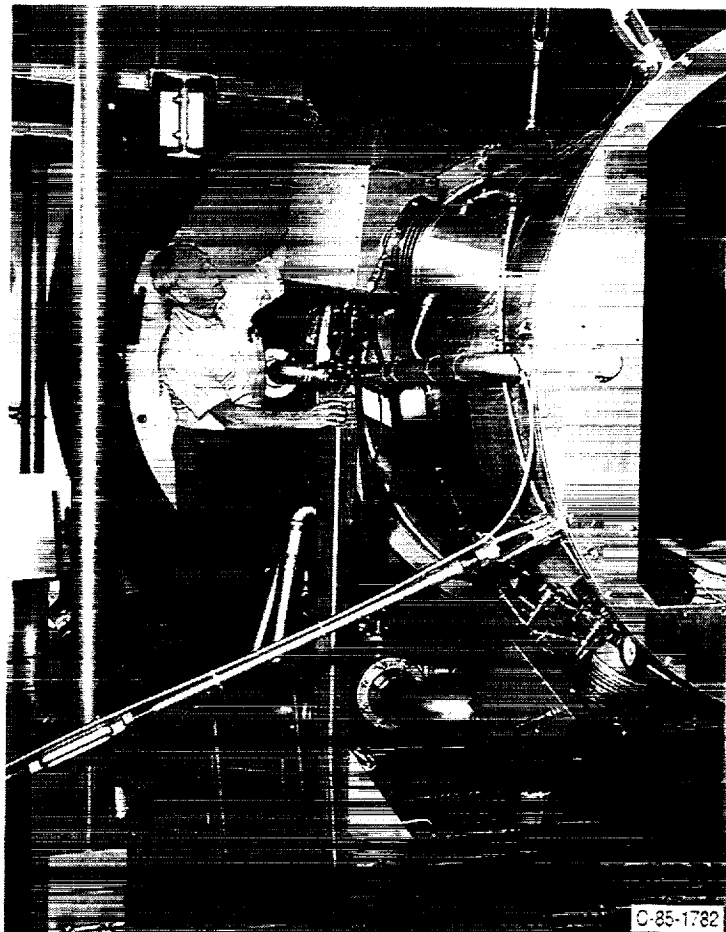


(C) MOUNT INSTALLED.

FIGURE 9—SAPPHIRE WINDOW MOUNT.



(A) SCHEMATIC.



(B) PHOTOGRAPH.

FIGURE 10.—INFRARED CAMERA ENCLOSURE AND MOUNT SYSTEM.

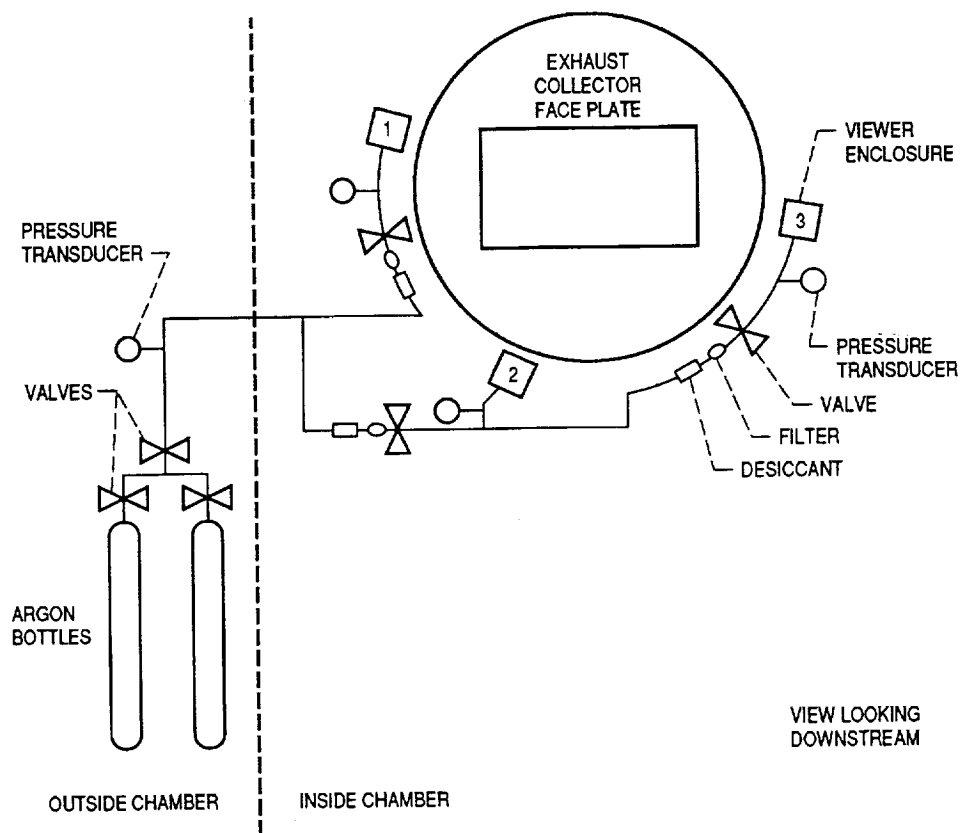
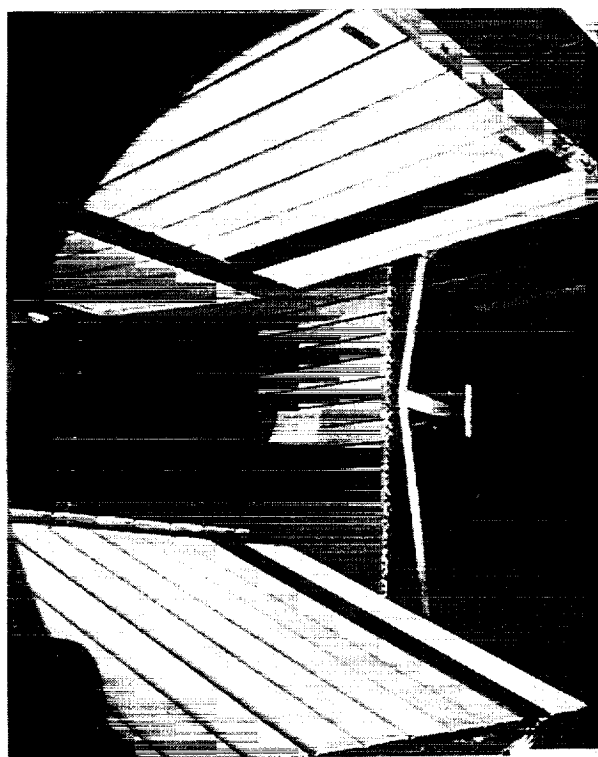
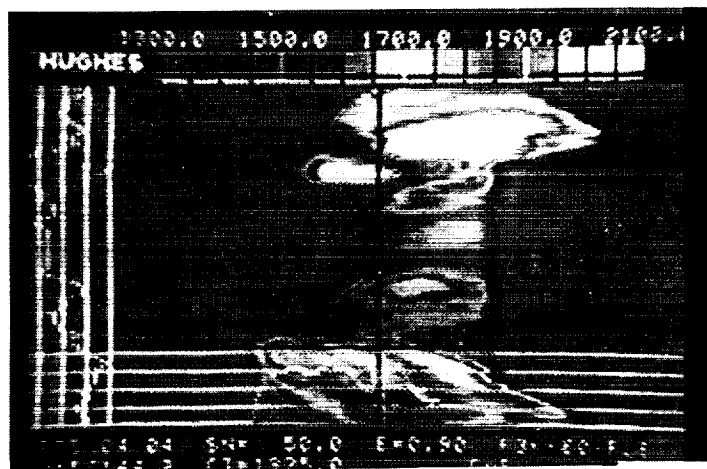


FIGURE 11.—ARGON DISTRIBUTION SYSTEM.



(A) VISUAL IMAGE.

MACH NUMBER 0.8
 ALTITUDE, m (ft) 7.315 (24 000)
 NOZZLE VECTOR ANGLE, deg 9



(B) INFRARED IMAGE.

FIGURE 12.—TYPICAL INFRARED IMAGE VIEW FROM CAMERA PORT 3.

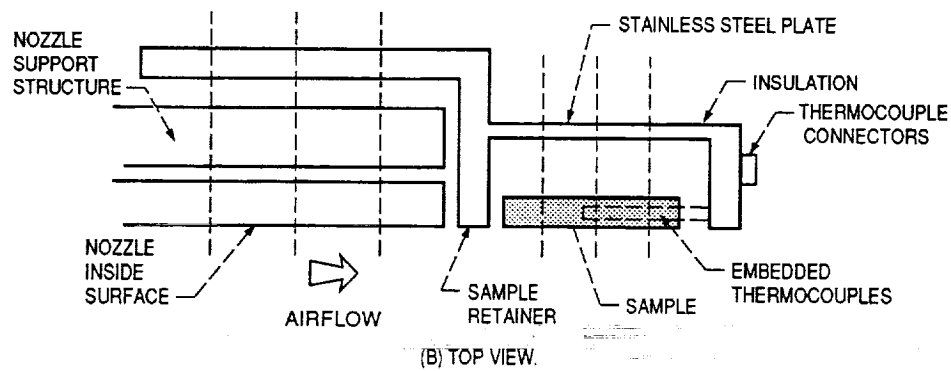
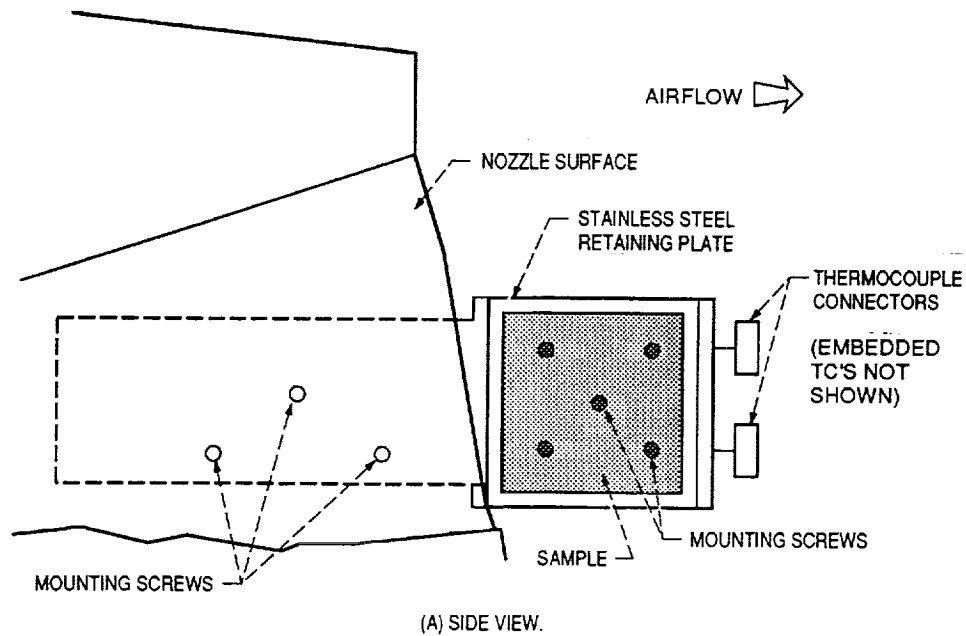


FIGURE 13.—REFERENCE TARGET.

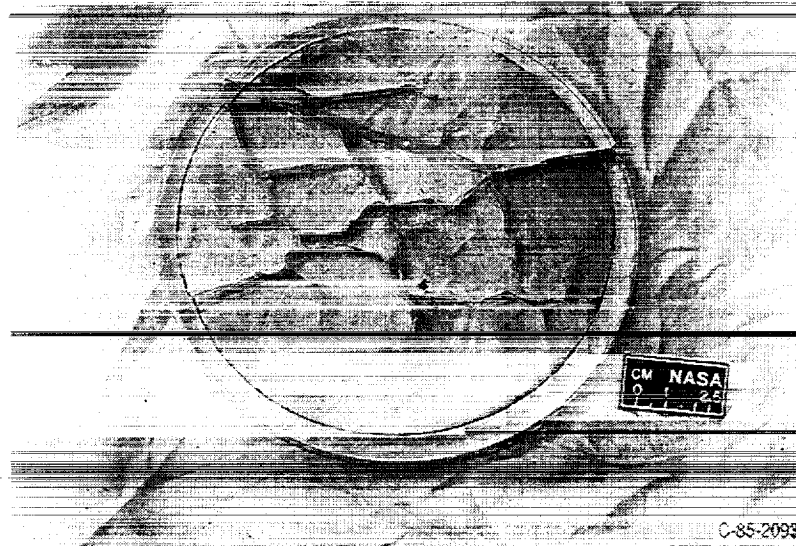


FIGURE 14.—SHATTERED SAPPHIRE WINDOW.

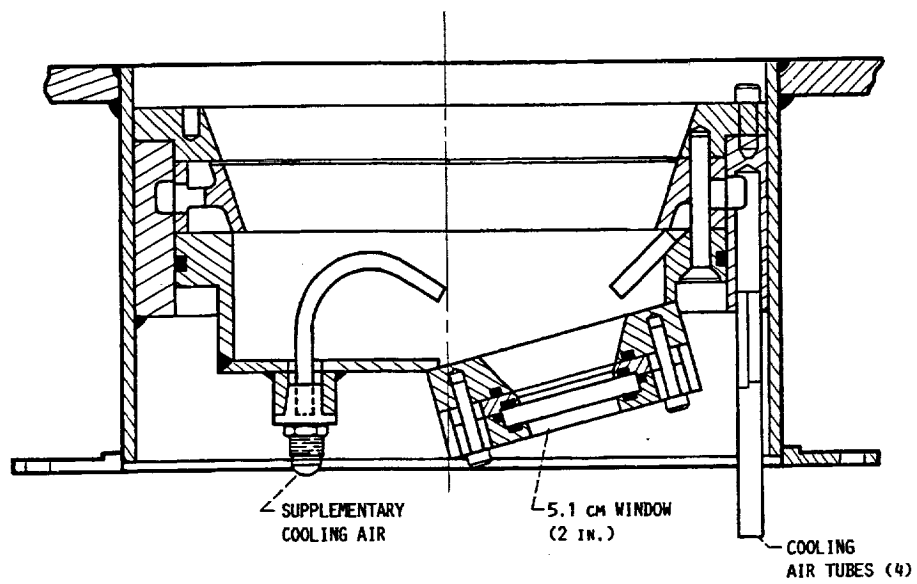


FIGURE 15.—MODIFIED WINDOW MOUNT.

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13. ABSTRACT (Maximum 200 words) This report details the use of infrared imaging for temperature measurement and thermal pattern determination during simulated altitude engine testing in the NASA Lewis Propulsion Systems Laboratory. Three identical argon-cooled imaging systems were installed in the facility exhaust collector behind sapphire windows to look at engine internal surfaces. The report describes the components of each system, presents the specifics of the complicated installation, and explains the operation of the systems during engine testing. During the program, several problems emerged, such as argon contamination system, component overheating, cracked sapphire windows, and other unexplained effects. This report includes a summary of the difficulties as well as the solutions developed. The systems performed well, considering they were in an unusually harsh exhaust environment. Both video and digital data were recorded, and the information provided valuable material for the engineers and designers to quickly make any necessary design changes to the engine hardware cooling system. The knowledge and experience gained during this program greatly simplified the installation and use of the systems during later test programs in the facility. The infrared imaging systems have significantly enhanced the measurement capabilities of the facility, and have become an outstanding and versatile testing resource in the Propulsion Systems Laboratory.				
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